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Groundwater Banking within the San Luis-Delta Mendota Water Authority Service Area

A Technical Feasibility Report

submitted to the:

San Luis-Delta Mendota Water Authority

by the:

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July 2000

1.0 Introduction

Scan the horizon from the Tracy Pumping Plant and the outlook is far from clear. A wet year in the Central Valley watershed once offered the promise of a bountiful water supply for farmers on the west side of the San Joaquin Valley. Now newspaper headlines report that the U.S. Bureau Reclamation anticipates making less that full contract deliveries to Westside farmers, even in wet years. This shift can be traced to the profound changes that have taken place in the way water is managed in California. New policies, new imperatives, and new rules have created water supply uncertainty within certain regions of the San Luis-Delta Mendota Water Authority service area. In keeping with their reputation for innovation, however, water managers and water users in the region continue to seek out new and creative strategies for dealing with uncertainty. This feasibility study was motivated by this search.

Since November of 1994, the San Luis-Delta Mendota Water Authority, the Westlands Water District, the U.S. Bureau of Reclamation, the California Department of Water Resources, the University of California at Berkeley, and the Natural Heritage Institute have been implementing the "Collaborative Field Demonstrations of the Efficacy and Practicality of Financial Incentives for Water Conservation in Agriculture" project. Funded as part of the U.S. Bureau of Reclamation Challenge Grant Program, these

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partners have collectively demonstrated how water transfers can maximize the economic benefits produced by an increasingly scarce and unreliable water supply. While the integrated nature of the water distribution system in the Authority's service area facilitates trading across great distances, the program has been limited by an inability to trade across time. This feasibility study was initiated to investigate how opening up the possibility of inter-temporal storage within the Authority would increase the net economic benefits accrued by water users and water districts participating in a water trading program.

The key physical requirement for a program of inter-temporal water storage is the availability of a water-banking site. Recent work on the promise of banking water in dewatered aquifers raises the question of whether any technically and economically viable groundwater banking sites can be identified within the Authority's service area. This technical feasibility report describes the results of a suite of analyses designed to respond to this question. *The objective of these analyses was to identify locations within the Authority's service area where it is physically possible to carry out a program of groundwater banking, and to evaluate the physical and economic feasibility of the banking arrangement.*

2.0 Geographic Scope

The San Luis & Delta-Mendota Water Authority provides water to member agencies on the west side of the San Joaquin Valley and in the Santa Clara Valley. These member agencies are responsible for delivering water to the retail water customer. The Authority's primary role is to serve as the operator of the major storage and distribution works that convey water to these agencies from pumping plants located in the Delta. The unifying feature of all of the SL&DMWA member agencies is that they contract with the U.S. Bureau of Reclamation for the delivery of Delta export water, the right to which is held by the Federal Central Valley Project (CVP).

As member agencies in the Santa Clara Valley serve an increasingly urbanized customer base, they have been relatively immune from difficulties posed by constraints on Delta exports. On the other hand, some of the agricultural water districts on the west side of the San Joaquin Valley bear the heavy burden of decreased supply reliability. In keeping with this disparity, the geographic scope of this investigation is limited to the portion of the west side of the San Joaquin Valley located within the Authorities service area (Figure 1). From north to south this region runs from T.2S. through to T.22S. The width of the region ranges from two to five 36 mi^2 townships. The heavy black border in Figure 1 will be included on a number of subsequent figures included in this report and should serve as a visual reference in those cases. The township and range numbering system is included on this figure to facilitate the interpretation of figures that follow later in this report. Several important physiographic features are depicted on Figure 1, including the points of emergence of major creeks from the adjacent Coast Range Mountains, which generally correspond with the apexes of their associated alluvial fans. In order to facilitate references to these alluvial fans later in the report, the geographic coordinates of the fan apexes are listed in Table 1.

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Figure 1: Geographic Scope of the Investigation

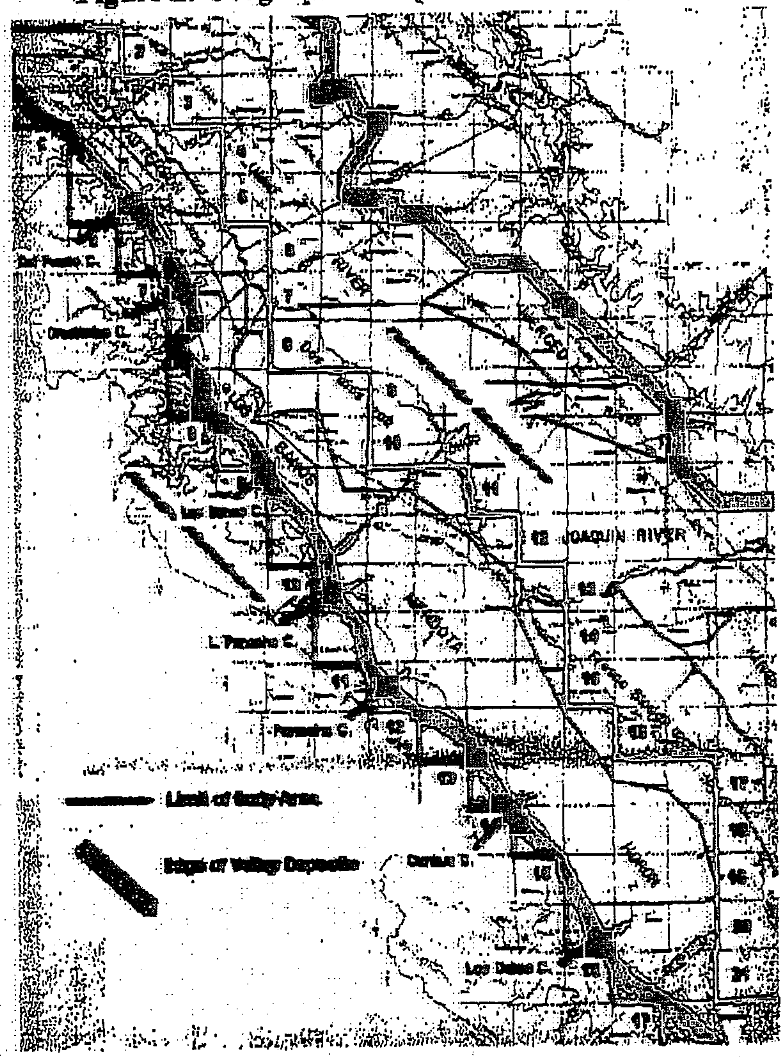

Table 1: Geographic Coordinates of the Apexes Alluvial Fans

Alluvial Fan	General Location of Fan Apex
Del Puerto Creek	T.5S. R.7E.
Orestimba Creek	T.7S. R.8E.
Los Banos Creek	T.10S. R.10S.
Little Panoche Creek	T.13S. R.11E.
Panoche Creek	T.15S. R.12E.
Cantua Creek	T.17S. R.15E.
Los Gatos Creek	T.20S. R.17E.

3.0 Geologic Setting

The San Joaquin Valley constitutes approximately the southern two thirds of California's Central Valley that is bounded on the east by the Sierra Nevada Mountains and on the

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west by the Coast Range. The San Joaquin River and its tributaries, which join the Sacramento River system in the Sacramento-San Joaquin Delta, drain the northern portion of the valley while the southern end coincides with the closed Tulare Lake Basin.

Between the surrounding topographic highs, the valley floor can be categorized into four geomorphic units: 1) dissected uplands, 2) alluvial fans, 3) river flood plains and channels, and 4) overflow lands and lake bottoms (Davis et al. 1957). Within the study area on the west side of the San Jaoquin Valley, only the first three units are of major significance. Of these, the alluvial fans represent the most important structures in terms of identifying potential groundwater banking sites. West side alluvial fans form a continuous strip running nearly 200 miles from the Delta to the southern terminus of the valley with widths ranging from less than 1 mile in the north to over 22 miles in the south. The upper slopes of west side alluvial fans are relatively steep with their associated streams incised up to 5 or 10 feet. Lower fan slopes are relatively gentle and are essentially undissected by streams channels. Much of the irrigated agriculture in the Authority's service area takes place in the lower fan regions.

The source material for west side alluvial fans, the Coast Range, are composed of complexly folded and faulted, primarily marine Jurassic-Cretaceous, and marine and mon-marine Cenozoic sedimentary rocks, the Franciscan metamorphic assemblage, and some igneous bodies (Jennings 1977, Miller et al. 1971). In general the watersheds of the intermittent streams associated with the alluvial fans (identified in Figure 1) extend farther into the Coast Range than drainages that supply sediment to the interfan regions in the form of mudflows and debris flows. The higher sediment transport potential of the intermittent streams is associated with an increase in the amount of coarse-grained material in the alluvial fans relative to the interfan regions. Within alluvial fans, Quaternary alluvium generally ranges from sandy loams in the upper fan region to loams and clay loams down slope. The outer rim of the alluvial fans in the trough of the valley is generally underlain by a shallow water table and processing a high concentration of soluble salts.

With increasing depth within these alluvial fans the Quaternary alluvium gives way to the Corcoran Clay Member of the Tulare Formation. The Corcoran Clay was deposited across a large lakebed and can be traced in the sub-surface over a distance of over 200 miles from the Delta in the north to Kern County in the south. The average width of the formation is 25 miles. The thickness of the clay ranges form as little as 10 feet along the edges of the formation to as much as 160 feet below the present Tulare Lake Bed. In general the thickest portion of the clay is aligned roughly with the present valley trough.

Texturally the Corcoran Clay is a well sorted silty-clay that is markedly free of sand over much of its lateral extent, with a relatively high porosity and a low permeability. Along the edges, however, it grades into coarser material prior to pinching out. The configuration of the western margin of the Corcoran Clay is depicted in Figure 2, along with the contour elevation of the top of the unit. One important feature of Corcoran Clay is that it generally curves towards the trough of the valley in the vicinity of the point of emergence of the major intermittent streams draining the Coast Range. This feature is

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most pronounced in the southern portion of the Authority's service area where Panoche, Cantua, and Los Gatos Creeks likely deposited deltas of coarse-grained material into the lake associated with the deposition of the Corcoran Clay. This feature of the Corcoran Clay provides for an exciting groundwater banking strategy that is described in greater detail later in this report.

Figure 2: Map of the Corcoran Clay in the Western San Joaquin Valley Elevation of the Top of the Formation and a Delineation of its Western Margin

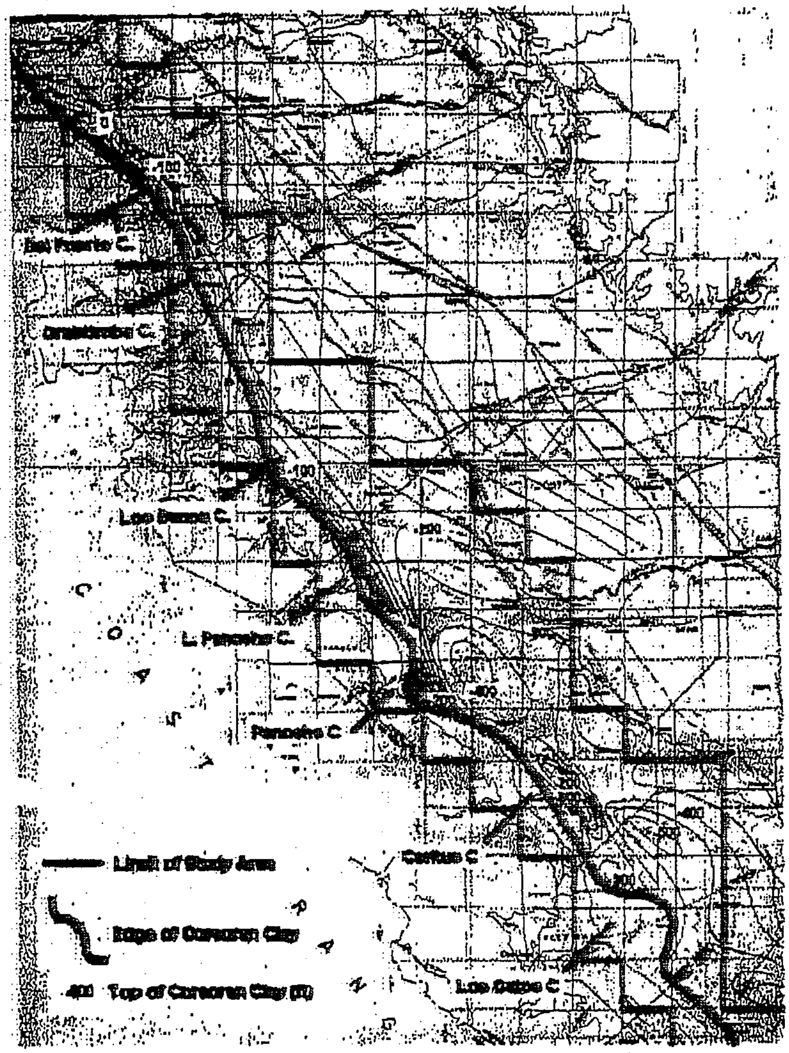

Figure 2 also reveals that below the Panoche Creek alluvial fan the Corcoran Clay has been deformed into an anticline that drops as much as 400 feet below sea level. As a result the margin of the Clay in this area is tilted up. Below the present Cantua Creek fan apex, however, the Corcoran Clay has been structurally warped into a syncline that rise to an elevation of –200 ft (MSL). Here the margin of the Corcoran Clay plunges dramatically towards the west. The condition of the Corcoran Clay below Los Gatos

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Creek alluvial fan is less clear. Here small synclinal structure on the western margin of the clay seem to give way to a major structural trough further to the east.

Historically, many of the agricultural production wells in the Authority's service area have been perforated below the Corcoran Clay. With the exception of the Firebaugh Canal Water Company, the Tranquility Irrigation District, and the extreme southeast portion of the Westlands Water District where clean sands of Sierra Nevada origin comprise the bulk of the overlying unconfined aquifer, the vast majority of installed water wells draw water from a confined aquifer below the Corcoran Clay (Gronberrg and Belitz 1992). The lower confined aquifer below the clay consists of poorly consolidated flood plain, deltaic, alluvial fan, and lacustrine deposts of the Tulare Formation. The parent material for these deposits lie in both the Coast Range and Sierra Nevada Mountains and while the exact origin at any location is difficult to determine and the exact drainage patterns during deposition may have been dramatically different then the current configuration. Throughout most of the area the lower confined aquifer has good hydraulic continuity both laterally and vertically.

4.0 Technical Workplan

To determine where and how aquifer storage and recovery operations might proceed in the Authority's service area, regional scale investigations into the following topics were pursued:

- Aquifer physical characteristics;
- Water quality patterns for native and stored groundwater; and
- Water conveyance constraints and opportunities.

The specific tasks associated with each investigation are described in the following sections.

4.1 Aquifer Physical Characteristics

- Map the current water table surface using the best available data and calculate the available storage capacity at potential banking sites.
- Determine the lateral extent and continuity of promising water bearing units.
- Estimate the hydraulic properties and infiltration rate of promising aquifer recharge/storage sites.
- Develop a simple mass balance model of promising groundwater banking sites to evaluate how aquifer storage might change in response to both natural and induced inflow and outflow from the system.

4.2 Water Quality Patterns

- Analyze water quality data in the native groundwater and in imported surface water to evaluate whether storage in the groundwater banking site will lead to a significant changes in the quality of either native or stored groundwater.

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- Evaluate whether these changes will create unacceptable water quality constraints for either the users of the native groundwater or the potential recipients of stored groundwater.

4.3 Water Conveyance Constraints and Opportunities

- Describe the constraints and opportunities that existing conveyance structures pose for storage and recovery at promising groundwater banking sites.
- Propose alternative conveyance options that could remove constraints and enhance opportunities for groundwater banking within the Authority's service area.

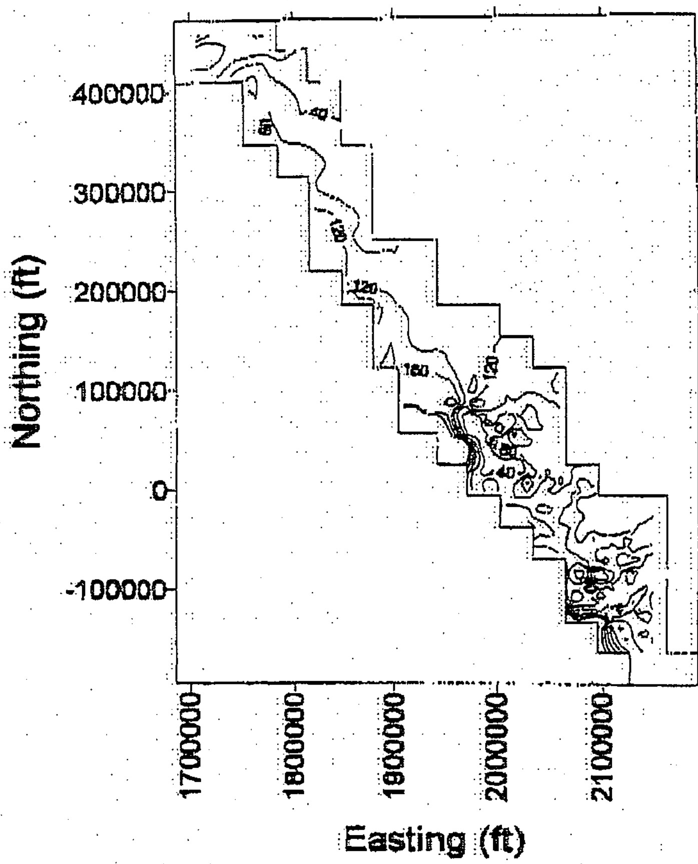
5.0 Aquifer Physical Characteristics

Section 4.1 describes the step that were undertaken to evaluate the physical suitability of aquifer material in the Authority's service area for a program of groundwater banking. The results of these analytical steps are included in the following sections.

5.1 Water Table Surface Elevation

The Department of Water Resources (DWR) regularly monitors water table surface elevations across California. In general, each well in the survey is monitored two time per year, once during the spring when the water table is presumably at its highest and once during the autumn when it would be most drawn down. Owing to the relatively long sampling cycle (over three months) and potential measurement error created by nearby groundwater pumping, contour maps developed with the data generally are not completely smooth as is seen for the Fall 1998 survey in Figure 3. Data from this survey can be used, however, to identify the prominent water table closed depression features located with in the Authority's service area. These are highlighted in Figure 4A.

Figure 3: Water Table Elevations During the Fall 1998 DWR Survey

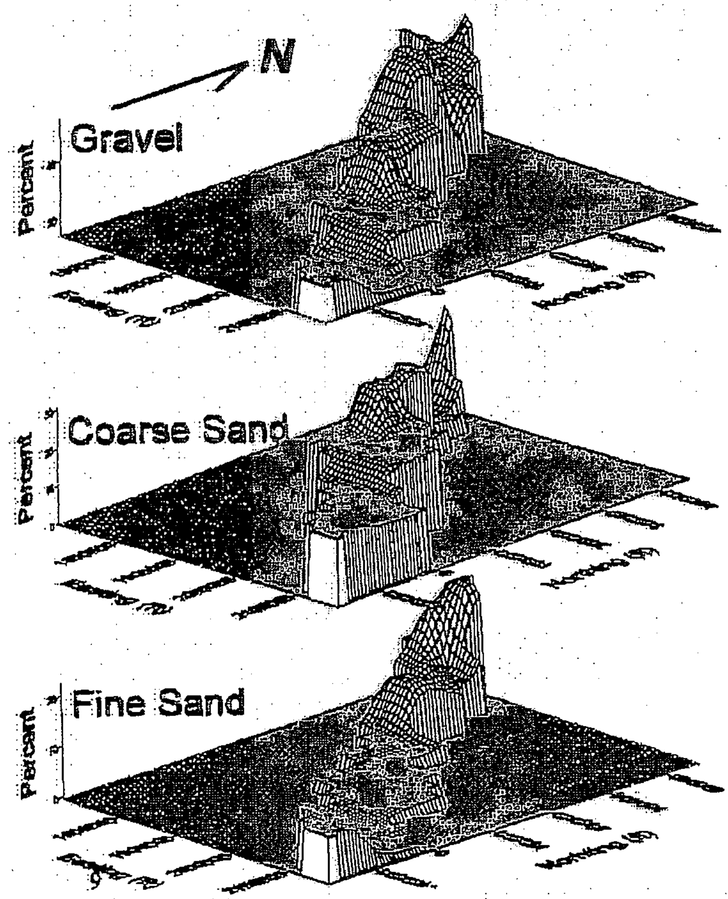


It is important to note, however, that the depression along the western margin of the valley is persistent. While the dimensions of the feature may vary with time, local hydrogeologic controls on the feature likely cause to persist. Figure 2 suggests that it is in this region the Corcoran Clay formation pinches out, eliminating the flow-impeding horizon that has caused the water table to rise so dramatically further to the east. The hypothesis is that this is the recharge zone for the confined aquifer below the Corcoran Clay and that a state of quasi-equilibrium has been reached between these depressions and the level of groundwater pumping from the confined aquifer further down the alluvial fans. If this hypothesis is correct, this drawdown feature offers an exciting recharge and recovery opportunity that is discussed in greater detail below.

5.2 Lateral Extent and Continuity of Promising Water Bearing Units

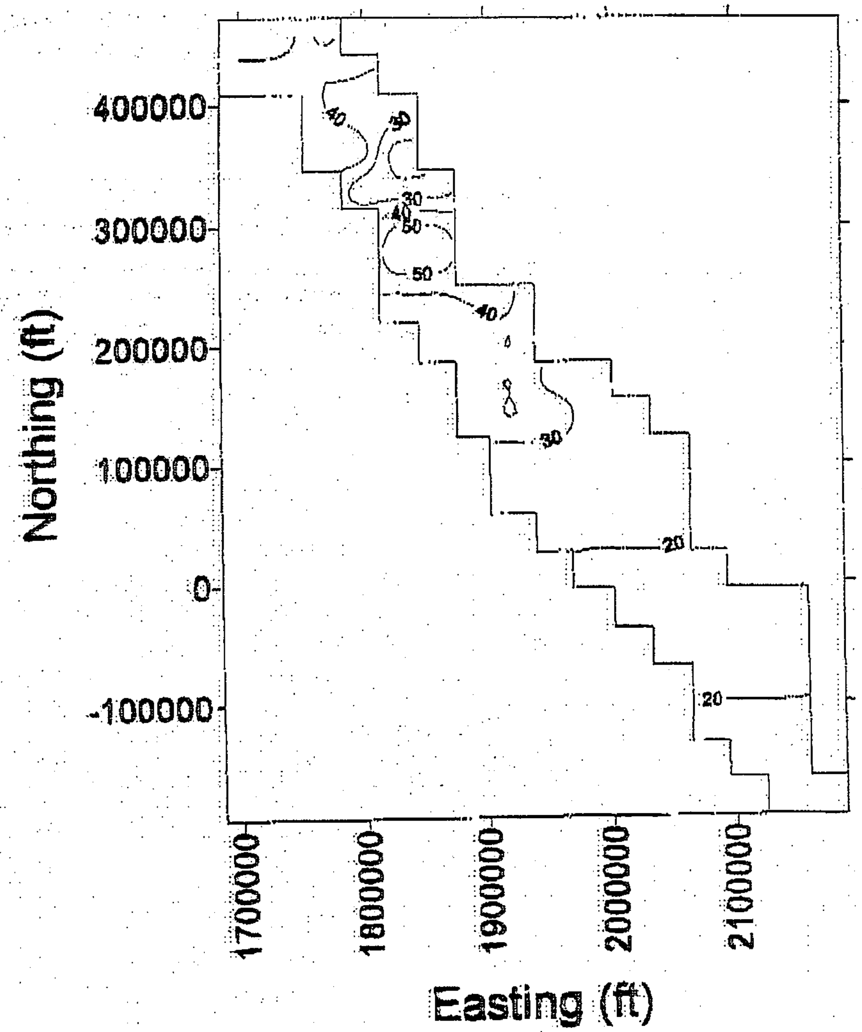
In general, the ideal aquifer storage and recovery region will be characterized by a high percentage of coarse-grained material in the subsurface. In alluvial fan systems these coarse-grained material are generally associated with stream and channel deposits laid down during fan formation. As a rule the materials will be more prevalent in the upper regions of a given alluvial fan and in alluvial fans associated with relatively large streams. Both occurrences are associated with the higher sediment transport potential of rapidly flowing streams. Figure 5 depicts the percentage of gravel, coarse sand, and fine sand contained within the too 200 ft of material in the subsurface below the Authority's service area based on USGS analysis of 422 well logs.

Figure 5: Textural Analysis of the Authority's Service Area



One of the most striking implications of Figure 5 is that, based on texture alone, the alluvial fans are indeed more suited to groundwater banking than the interfan regions. The local high points on each surface in the figure are located with the fans while the lows lie below interfan regions. In terms of evaluating the individual fans, the structures in the northern region of the Authority's service area generally seem to contain a higher percentage of gravel. Towards the southern end of the service area, coarse sand makes up the largest percentage of coarse-grained material. This pattern of textural composition suggest that on the basis of texture alone the northern regions may prove most suitable for groundwater banking. A more appropriate measure of suitability, however, may be the total percentage of coarse-grained material. Based on the data in Figure 5, the total percentage of coarse-grained material in the top 200 feet of aquifer can be calculated. These values are shown in Figure 6.

Figure 6: Total Percentage of Coarse-Grained Material in the Top 200 ft below the Authority's Service Area



The highest percentage of coarse-grained material is associated with the Orestimba Creek alluvial fan (see Figure 2) where over 50% of the material is either sand or gravel. The Los Banos Creek fan also contains a relatively high percentage of coarse-grained material. Further to the south the Little Panoche Creek and Panoche Creek fans contain between 20 and 30% coarse-grained material while the Cantua Creek and Los Gatos Creek fans contain approximately 20% coarse-grained material. It should be pointed out, however, that the prominent water table depression features do not extend as far north as the Orestimba Creek and Los Banos Creek fans (see Figure 4).

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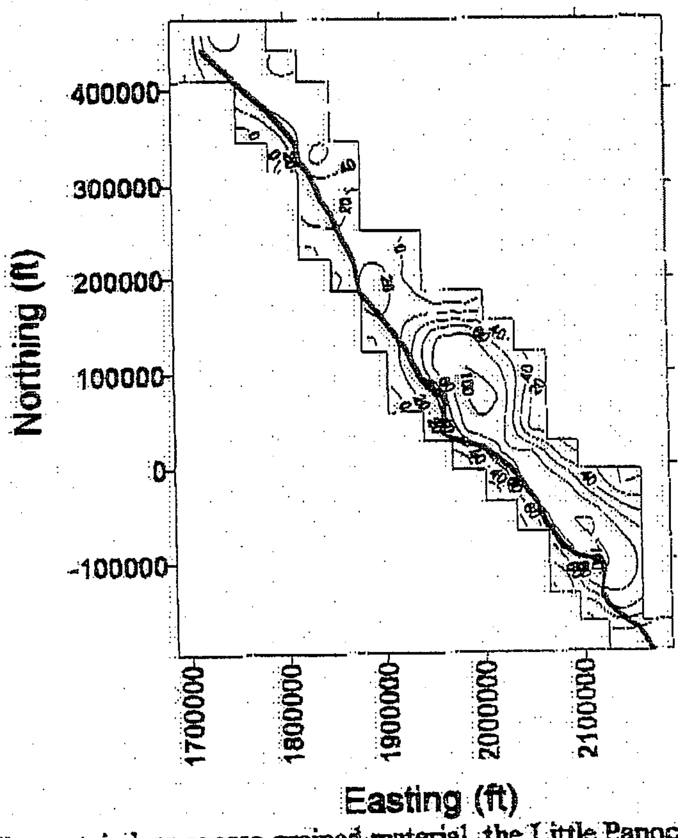
5.3 Aquifer Physical Properties

The textural composition of a region translates to several important physical parameters that can be used to assess the suitability of a particular region for groundwater banking. The soil permeability controls the rate at which water can be recharged to an underlying aquifer through recharge basins located at the ground surface. The specific yield controls the amount of water that can be stored in a given volume of aquifer material. These parameters are discussed in greater detail in the following sections.

5.3.1 Soil Permeability

One factor controlling the viability of groundwater banking is the ability to recharge water at the soil surface. This is controlled largely by the permeability of the material in the top 10 to 15 feet of the soil profile. The percent of permeable soil within the 36 mi^2 townships in the Authority's service area are shown in Figure 7.

Figure 7: Percentage of Soil Classified as Permeable at a Given Location within the Authority's Service Area

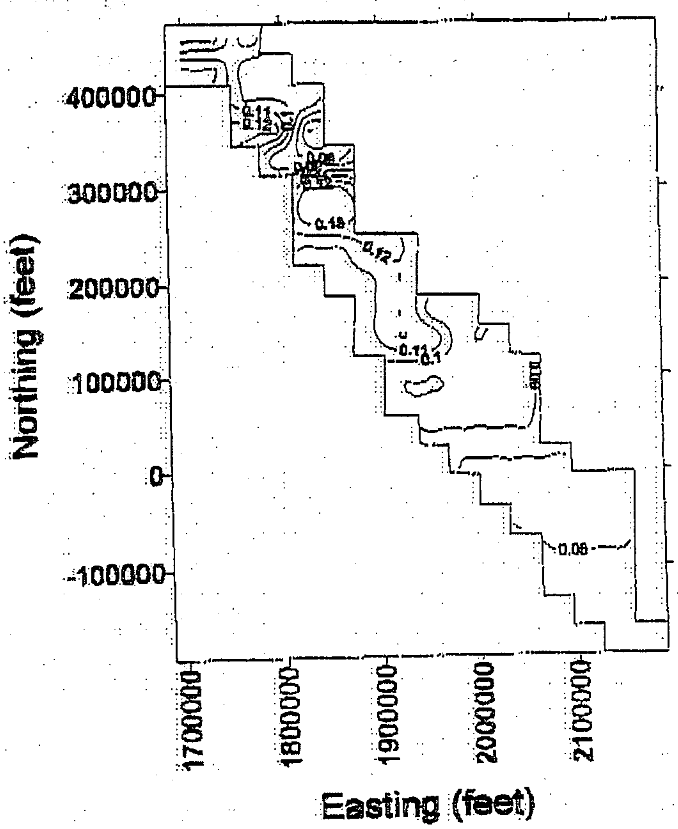


While they generally contain less coarse grained material, the Little Panoche Creek, Panoche Creek and Cantua Creek alluvial fans are comprised of material that weather to more permeable soil horizons than those in the north. In the mid-fan region of these structures, all soil is classified as permeable, grading to somewhat less permeable material in the fan apex and valley trough regions. Even in these zones, however, the percentage of permeable soil at a given location generally equals or exceeds that found in other part of the service area.

5.3.2 Specific Yield

The specific yield of an aquifer is a measure of the volume of water that can be stored within a unit volume of aquifer material. It is related to the overall porosity of the material and the ability of the material to retain water with the material matrix. A material with a high specific yield offers a large potential to store water within the unsaturated zone. In general, coarse-grained materials have a higher specific yield. The estimated specific yield within the service area is depicted in Figure 8.

Figure 8: Estimated Aquifer Specific Yield within the Authority's Service Area

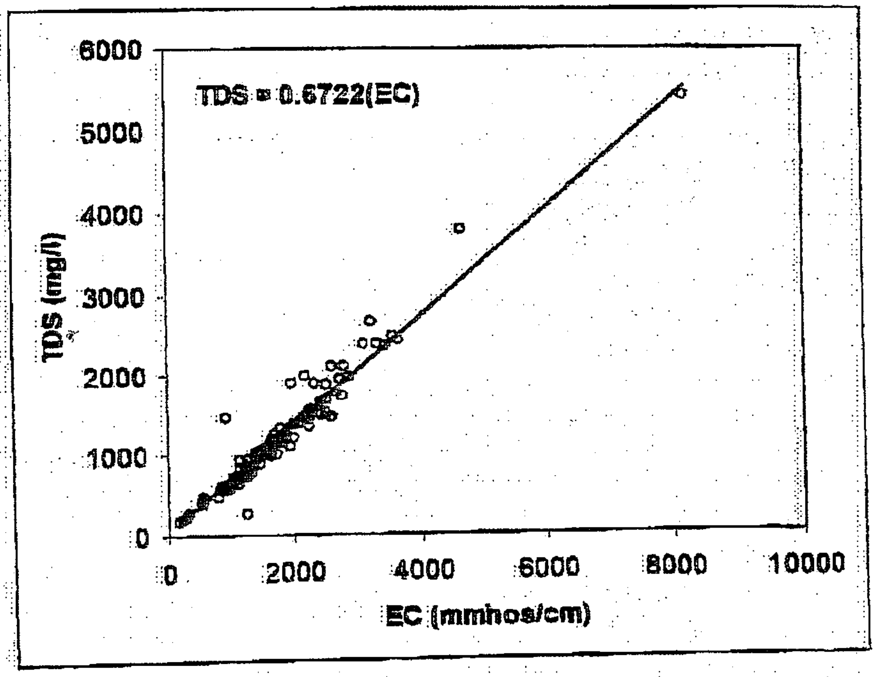


Once again the highest values, in excess of 0.18, are associated with the Orestimba Creek alluvial fan where the percentage of coarse-grained material is highest. Outside of this zone however, the parameter ranges form a high of 0.12 to a low of 0.08. The overall uniformity of the specific yield suggests that it is not the most important parameter in terms of assessing the suitability of a specific site.

6.0 Water Quality Patterns

The United States Geological Survey periodically compiles water quality measurements in the Central Valley. A number of constituents are reported in these databases, although not every well is tested for the full suite of constituents. One parameter that is reported for nearly every well at every sampling interval is the Electrical Conductivity (EC) of the well water. EC is a measure to the ease at which water conducts and electric current and it can be measure in the field using a simple and relatively inexpensive probe. This conductance is certainly related to the concentration of dissolved ionic solids but is also a function of the valence of the dominant ions in solution. For a given concentration of total dissolved solids (TDS) the EC will be higher in a solution dominated by Ca^{2+} cations that one dominated by Na^{1+}. In general, for a given water, TDS = A(EC) where A is a coefficient that generally lies between 0.54 and 0. 96 for natural waters (McCutcheon et al. 1993). For the 121 groundwater samples from the San Luis & Delta Mendota Water Authority where both EC and TDS were measured the coefficient value is 0.67 (Figure 9), well within the range of natural waters.

Figure 9: Relationship Between EC and TDS for Wells within the Authority's Service Area



Given the goodness of fit of this relationship, a value of TDS was calculated for each well where only EC was measured. This data were then separated into samples from the unconfined aquifer located above the Corcoran Clay and samples from the confined aquifer below that unit. The spatial distribution of water quality within these two aquifers is depicted in Figure 10. According to Figure 10, at any particular location in the Authority service area, the suitability of groundwater for use as irrigation water is generally better in the confined aquifer than in the overlying unconfined aquifer. The primary exception is on the eastern margin of the service area at a northing of approximately 100,000 ft. This area coincides roughly with the Tranquility area where the unconfined aquifer is contained largely within sands of a Sierran origin. Lower levels of dissolved ions than deposits typically characterize these materials than those with parent material from the Coast Range Mountains. The general reliance upon the unconfined aquifer for supplemental irrigation water is largely related to the differential in water quality.

Figure 10: Groundwater TDS within the Authority's Service Area for the Unconfined (A) and Confined (B) Aquifer Systems

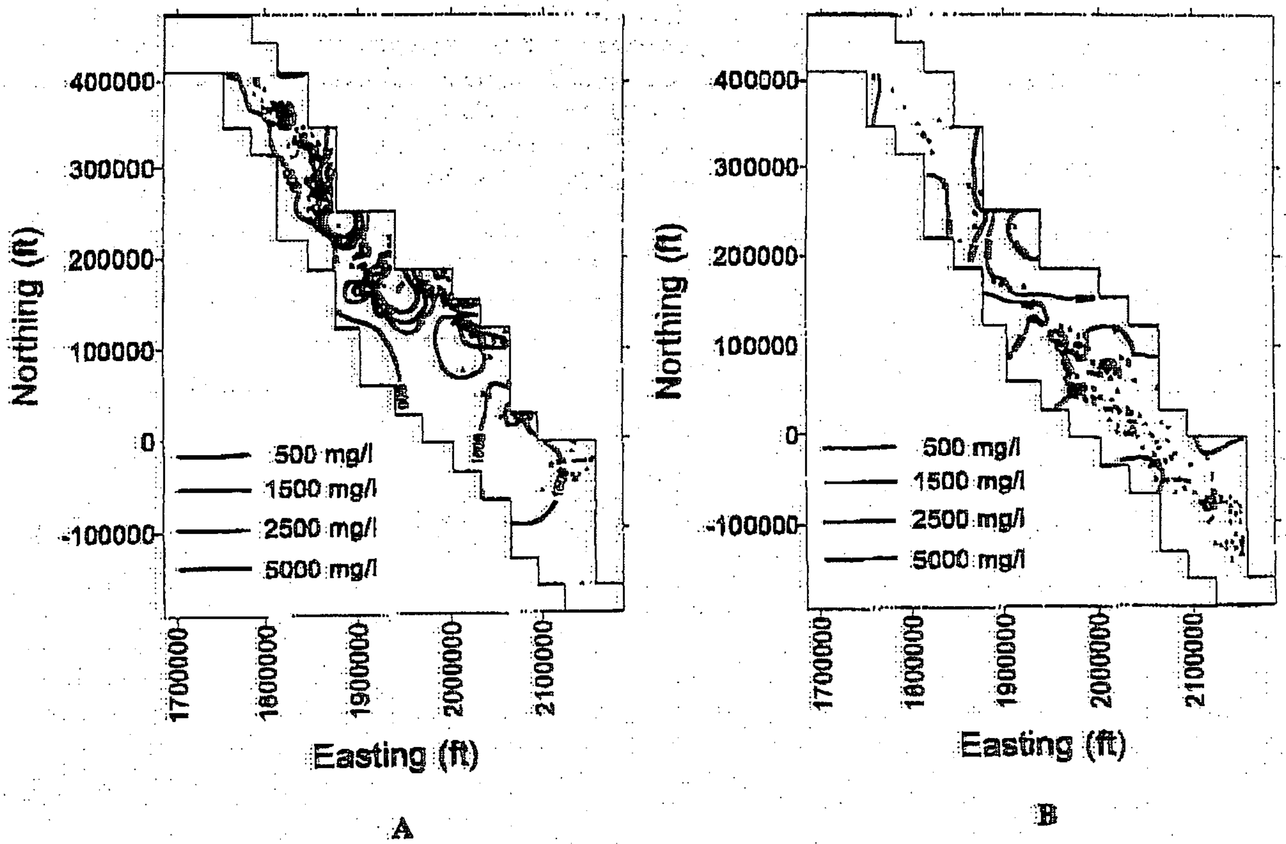
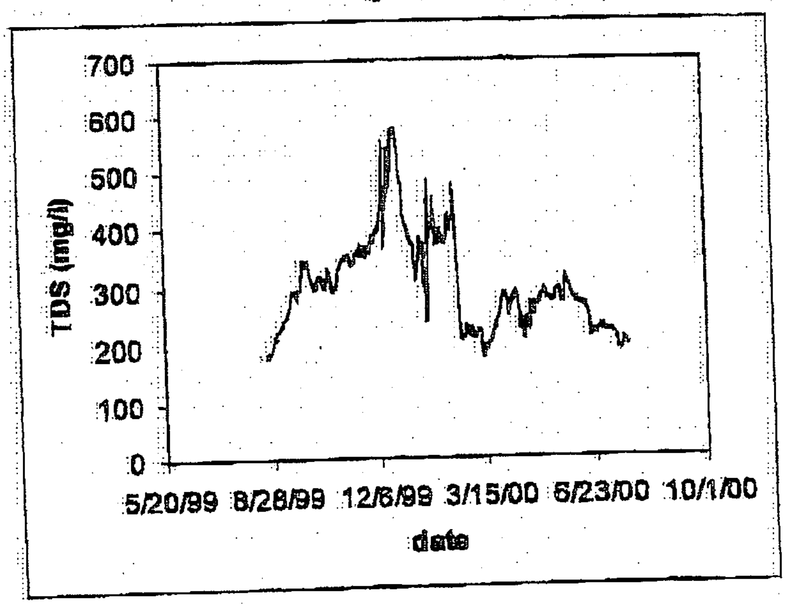


Figure 11: Surface Water TDS Measured at the Delta Export Pumps



The general conclusion that can be drawn from Figure 10 is that the groundwater quality within the Authority's service area is relatively poor. When compared with the quality of water that is imported to the region through the Delta pumps (Figure 11), the implication is that surface water banked within the service area would experience a decline in water quality. Over the course of the current water year, TDS measured at the Delta export pumps has varied between 200 and 600 mg/l. This water quality is superior to that found in groundwater with in the service area.

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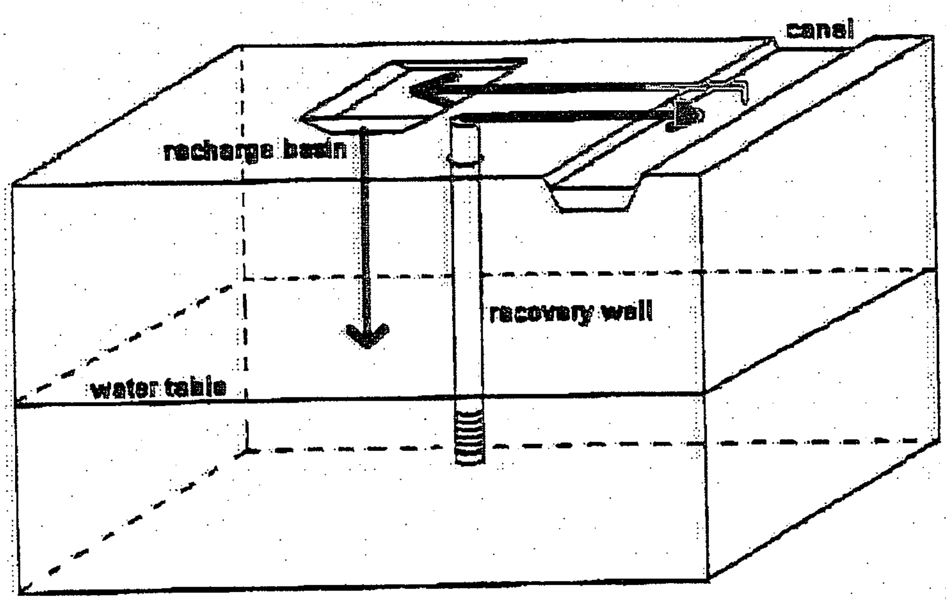
7.0 Water Conveyance Constraints and Opportunities

In the general formulation of an active groundwater banking project, water is conveyed to the recharge site via surface water delivery infrastructure and is recovered and delivered to end-users by re-introducing it to the same delivery system (Figure 12). Another type of groundwater banking program relies on *in lieu* exchanges whereby surface water is delivered during wet years to water users who typically rely on groundwater pumping for some portion of their supply. The forgone pumping is considered to be banked groundwater that can be recovered by these users though enhanced groundwater pumping during dry years (Figure 13). Both of these operational strategies create potential problems in portions of the Authority's service area.

Figure 12: Schematic Representation of Groundwater Banking Under an Active Storage and Recovery Strategy



... relatively poor groundwater quality (Figures 10 and 11)

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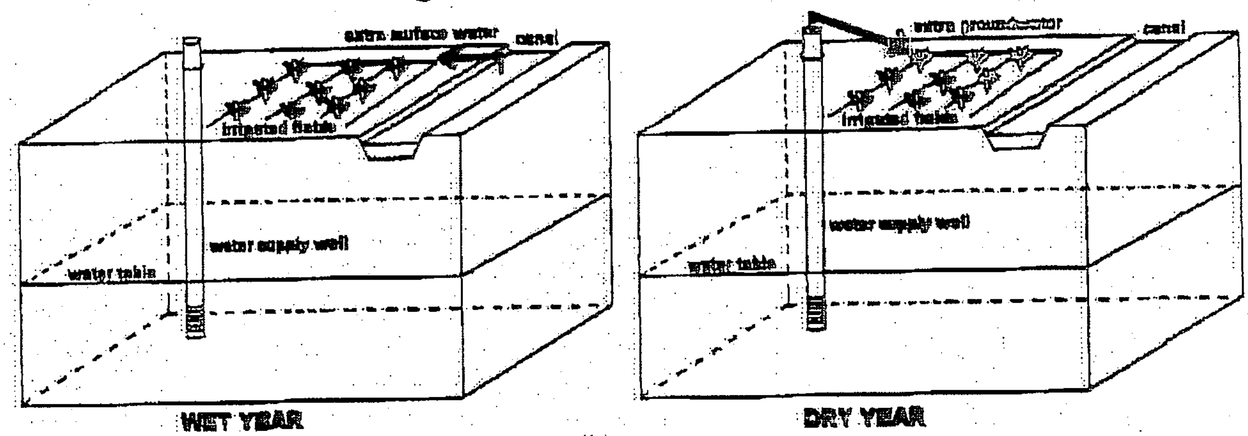
facilities. As groundwater pumping exerts an import hydrologic control on the volume of drain water generated within the service area, an *in lieu* recharge program based on an increased application of imported surface water would likely exacerbate existing drainage problems. Increasing the reliance on pumped groundwater during dry years could, on the other hand, assist in reducing drainage volumes.

Figure 13: Schematic Representation of Groundwater Banking Under an *In Lieu* Storage and Recovery Strategy



The unique set of condition in the Authority's service area create and opportunity to design a hybrid operational strategy that would avoid the problems associated with either a purely active or purely *in lieu* strategy. This program would work by using the existing San Luis Canal and new spur facilities to convey available water to recharge basin overlying the closed depressions on the western margin of the valley below the Little Panoche, Panoche and Cantua Creek alluvial fans. These depressions coincide with the recharge zone of the confined aquifer below the Corcoran Clay so that active recharge would result in a rise of the piezometric surface beneath the service area. This rise would allow for enhanced groundwater pumping during dry years in a manner akin to an *in lieu* exchange. If this higher level of pumping could be maintained in such a way that the piezometric surface does not experience any drawdown in excess of that associated with current levels of pumping then the program would directly improve the reliability of groundwater supplies, the central feature of an *in lieu* program.

In order to investigate the feasibility of this approach, a classic analytical solution to a confined aquifer flow problem was invoked (Chan et al. 1976). This solution describes the spatial and temporal response of the piezometric surface within a rectangular non-leaky, homogeneous, confined aquifer in response to pumping from a single well at a known location. It should be pointed out that analytical solutions typically apply to very stylized aquifer systems that generally depart from natural systems in a number of ways. In the case of the confined aquifers located below the Corcoran Clay within the alluvial fans of the western San Joaquin Valley these departures include:

- The fact that these aquifer are not rectangles with no flow conditions along the north and south margins,

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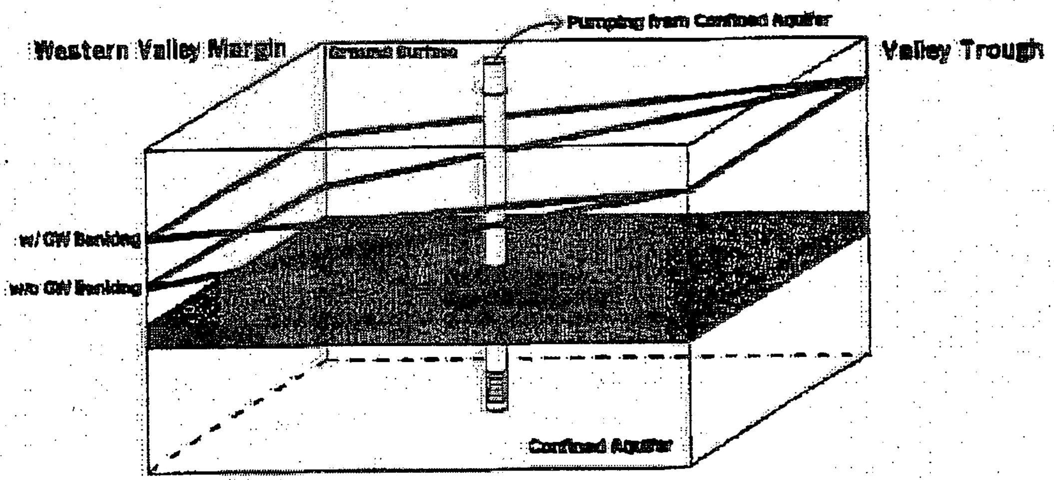
- The fact that the hydraulic properties within the confined aquifer are not homogeneous, and
- The fact that the Corcoran Clay does not eliminate leakance from the overlying unconfined aquifer system.
- The fact that pumping from confined aquifer does not occur through a single well.

Even with these simplifying assumptions, however, Chan's analytical solution allows for a preliminary screen on the feasibility of an *in lieu* recovery program in the Authority's service area. Should promising results motivate an interest in more refined analysis, the focus of investigation would shift to numerical modeling of the aquifer system that is free from these simplifying assumptions.

In the service area, Chan's solution can be formulated to describe the actual situation as depicted in Figure 14.

Figure 14: Schematic Representation of the Application of the Chan Solution to the Western San Joaquin Valley



Analysis conducted by the USGS (Belitz and Phillps 1992) confirms that the piezometric surface in the confined aquifer does slope towards the western margin of the San Joaquin Valley. Figure 15 depicts the 1984 position of the piezometric surface in the vicinity of the Little Panoche Creek, Panoche Creek and Cantua Creek alluvial fans, along with a regression line fit to the reported data.

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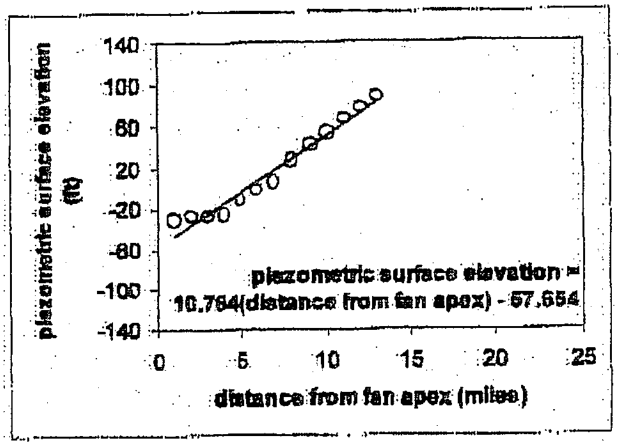
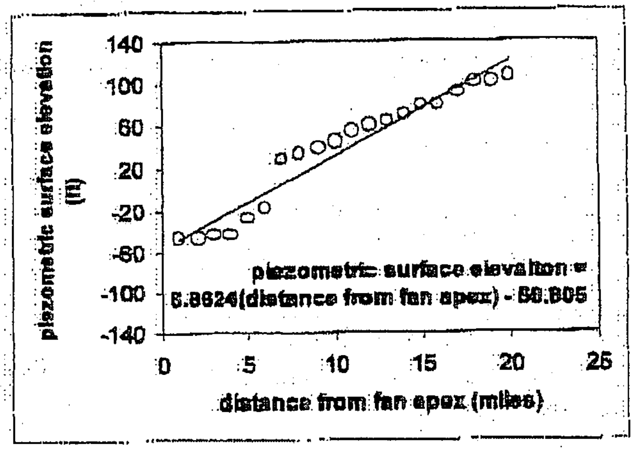
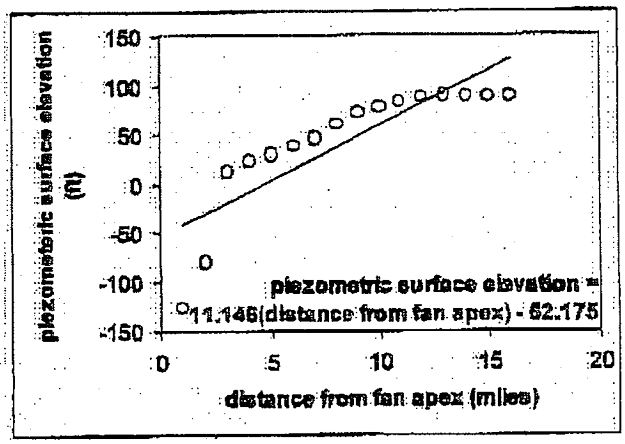
Figure 15: 1984 Piezometric Surface Elevation within the Little Panoche Creek (A), Panoche Creek (B) and Cantua Creek (C) Alluvial Fans

A



B





C

In each of the alluvial fans, the lowest piezometric surface elevation is located near the western margin of the San Joaquin Valley and is fairly well associated with the low water table elevation in the target closed depressions. Maps of these closed depression constructed from 1984 water level data reveal that below the western margin the water table elevation corresponds fairly well with the elevation of the peizometric surface (Figure 16). The correspondence supports the hypothesis that these depressions serve as the recharge area for the confined aquifer located below the Corcoran Clay.

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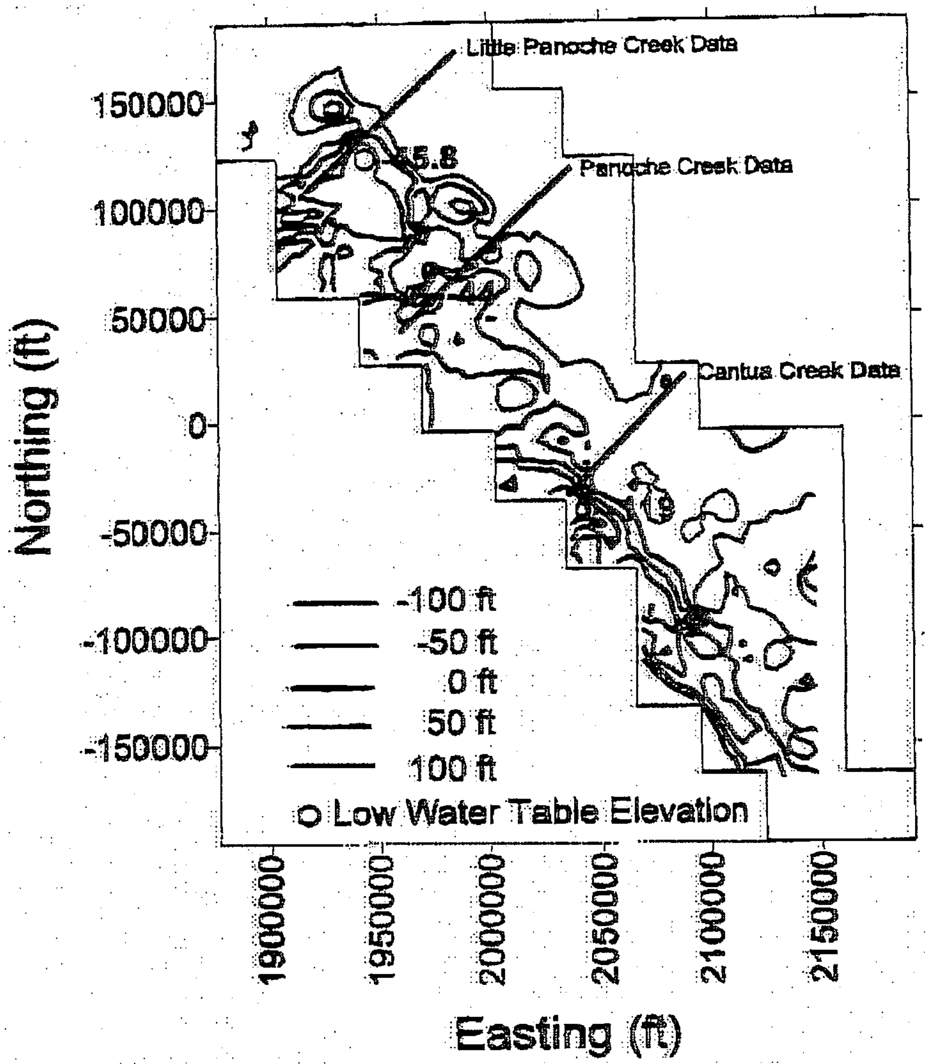
Figure 16: 1984 Configuration of Water Table Depressions on the Western Margin of the San Joaquin Valley



The operational strategy under evaluation using Chan is to raise the water table elevation in these target depression through active recharge, thereby raising the piezometric surface described using the regression model across the entire alluvial fan as depicted in Figure 15. Having made this adjustment it is possible to calculate how much pumping could be enhanced while maintaining a similar level of well drawdown as projected under the no groundwater banking scenario.

The Chan solution is captured in the following equation. Here the drawdown at any x,y point in a rectangular confined aquifer at time t is calculated as a function of the location of the pumping well, the pumping rate, and the hydraulic properties and geometry of the aquifer. The solution is obtained in the form of summations over two infinite series m and n.

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$$s(x,y,t)=\frac{xh}{a}+\frac{Q}{aT}\sum_{m=1}^{\infty}\frac{\sigma(\alpha_m,x,\xi)}{\alpha_m\sinh(\alpha_m b)}\{\cosh[\alpha_m(b-|\eta-y|)]+\cosh[\alpha_m(b-\eta+y)]\}-$$
$$\frac{2Q}{abT}\sum_{m=1}^{\infty}\frac{\exp(-T\alpha_m^2 t/S)}{\alpha_m^2}\sigma(\alpha_m,x,\xi)-$$
$$\frac{4Q}{abT}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\exp(-T\gamma_{m,n}^2 t/S)}{\gamma_{m,n}^2}\sigma(\alpha_m,x,\xi)c(\beta_n,y,\eta)$$

where

$Q =$ *well pumping rate*

$s =$ *drawdown*

$S =$ *storage cofficient*

$T =$ *transmissivity*

$\xi,\eta = x,y$ *coordinates of pumping well*

$a =$ *length of confined aquifer*

$b =$ *width of confined aquifer*

$h =$ *difference in piezometric surface across aquifer*

$$\alpha_m = \frac{m\pi}{a}$$
$$\beta_n = \frac{n\pi}{b}$$
$$\gamma_{m,n}^2 = \alpha_m^2 + \beta_n^2$$
$$\sigma(\alpha_m,x,\xi) = \sin(\alpha_m x)\sin(\alpha_m \xi)$$
$$c(\beta_n,y,\eta) = \cos(\beta_n y)\cos(\beta_n \eta)$$

Three major challenges confront the application of the Chan solution in the western San Joaquin Valley. These include:

1. Defining appropriate values for the hydraulic properties,
2. Defining appropriate rectangular aquifer geometries, and
3. Resolving the distributed nature of pumping from the confined aquifer onto a representative pumping well.

In terms of the hydraulic properties, the values of concern are the transmissivity (T) expressed in ft^2/day and the storage coefficient (S) expressed in ft/ft, or as a dimensionless parameter. Several authors have attempted to quantify these numbers for the confined aquifer below the western San Joaquin Valley. Williamson (1989) evaluated the texture and thickness of the confined aquifer and made the following estimates of hydraulic properties.

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Assume the hydraulic conductivity of coarse-grained material in the confined aquifer is 31.1 ft/day (equivalent to K associated with sands of Coast Range origin).

$$T_{min} = 7776 \quad ft^2/day$$
$$T_{max} = 31{,}968 \quad ft^2/day$$
$$T_{average} = 19{,}008 \quad ft^2/day$$

Assume the hydraulic conductivity of coarse-grained material in the confined aquifer is 103.7 ft/day (equivalent to K associated with Sierran sands).

$$T_{min} = 25{,}920 \quad ft^2/day$$
$$T_{max} = 106{,}272 \quad ft^2/day$$
$$T_{average} = 63{,}072 \quad ft^2/day$$

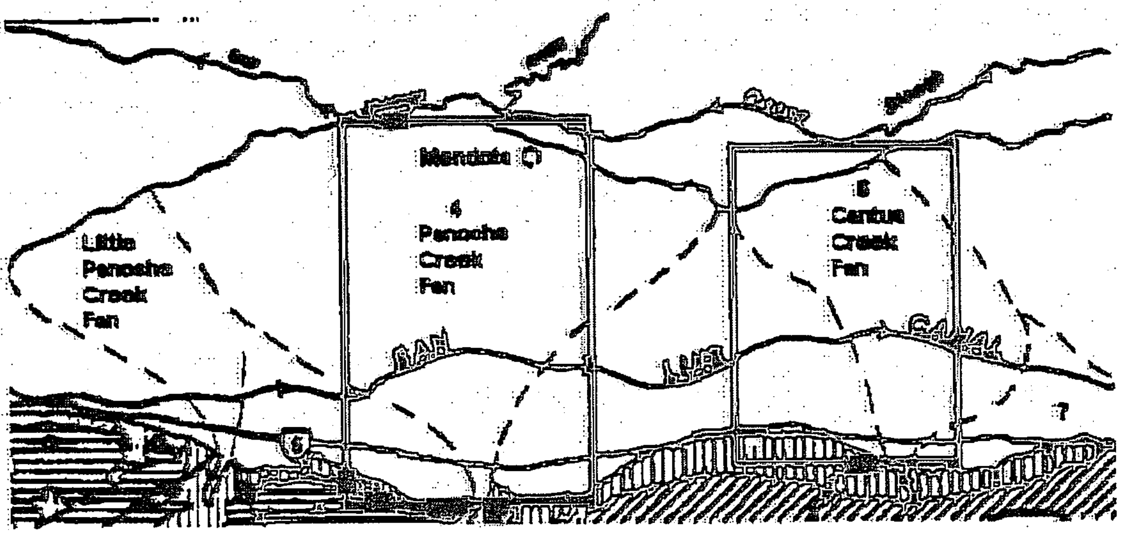
Assume the thickness of the confined aquifer is approximately 1000 ft across the western San Joaquin Valley.

$$S = 0.003$$

The values provide a range of appropriate values for use in the Chan solution applied within the Authority's service area.

In terms of defining appropriate rectangular geometries for the application of the Chan solution in region, an attempt was made to model the area associated with the major alluvial fans in the region with where pronounced drawdown features exist on the western margin of the valley. These include the Panoche and Cantua Creek alluvial fans. Rectangular aquifers that approximate the confined aquifers below these fans are shown in Figure 17.

Figure 17: Location of Chan Solutions Applied in the Western San Joaquin Valley



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The dimensions of these rectangular aquifers are 19 miles x 10 miles (100320ft x 52800 ft) for the Panoche Creek Fan and 15 miles x 10 miles (79200 ft x 52800 ft) for the Cantua Creek Fan. The transects of 1984 piezometric surface elevation data in Figure 15 lie roughly along the center of the long axis of each model. It should be pointed out that the drawdown features extend beyond the lateral limits of the representative rectangular aquifers. The implications of this fact are discussed below.

In terms of resolving distributed pumping in the region onto a representative pumping well, a series of reports published by the USGS provide useful insight. In developing a finite difference groundwater model in a portion of the Authority's service area, including the Little Panoche, Panoche, and Cantua Creek alluvial fans, the domain of the model was delineated into distinct water management units (Figure 18). For each of the units, Gronberg and Belitz (1992) carried out an annual mass balance in order to calculate the level of groundwater pumping within each unit. The analysis generated the following results.

Unit #	Unit Name	Groundwater Pumpage (ft)
1	Firebaugh	0.0
6	Tranquility	0.3
8	Panoche	0.0
9	Broadview	0.0
10	San Luis	0.4
11a	Westlands WT<10 ft	0.4
11b	Westlands 10ft<WT<20ft	0.46
11c	Westlands WT>20 ft, with surface water	0.25
11d	Westlands WT>20 ft, without surface water	2.46
12	Mendota Wildlife Refuge	0.0

These values were used to calculate pumping loads within three regions corresponding to the upper, middle and lower thirds of two rectangular confined aquifers associated with the Panoche and Cantua Creek alluvial fans (Figure 17). These values are contained in the following table.

	Base Groundwater Pumping (acre-feet/year)			
Model	Upper Fan Third	Middle Fan Third	Lower Fan Third	Total
Panoche	25280	13293	7834	46407
Cantua	23558	11072	12378	47008

These pumping loads where imposed on three representative wells pumping at the confined aquifer where the difference in the piezometric surface in the confined aquifer, h, was derived from the regression line fit to the 1984 data (Figure 15). For the Panoche Creek solution the value of h was set to 163 ft while in the Cantua Creek case, h equals 167 ft. A base case solution was obtained by imposing the existing pumping on the a confined aquifer with the estimated piezometric surface configuration and noting the predicted long-term pumping well drawdown.

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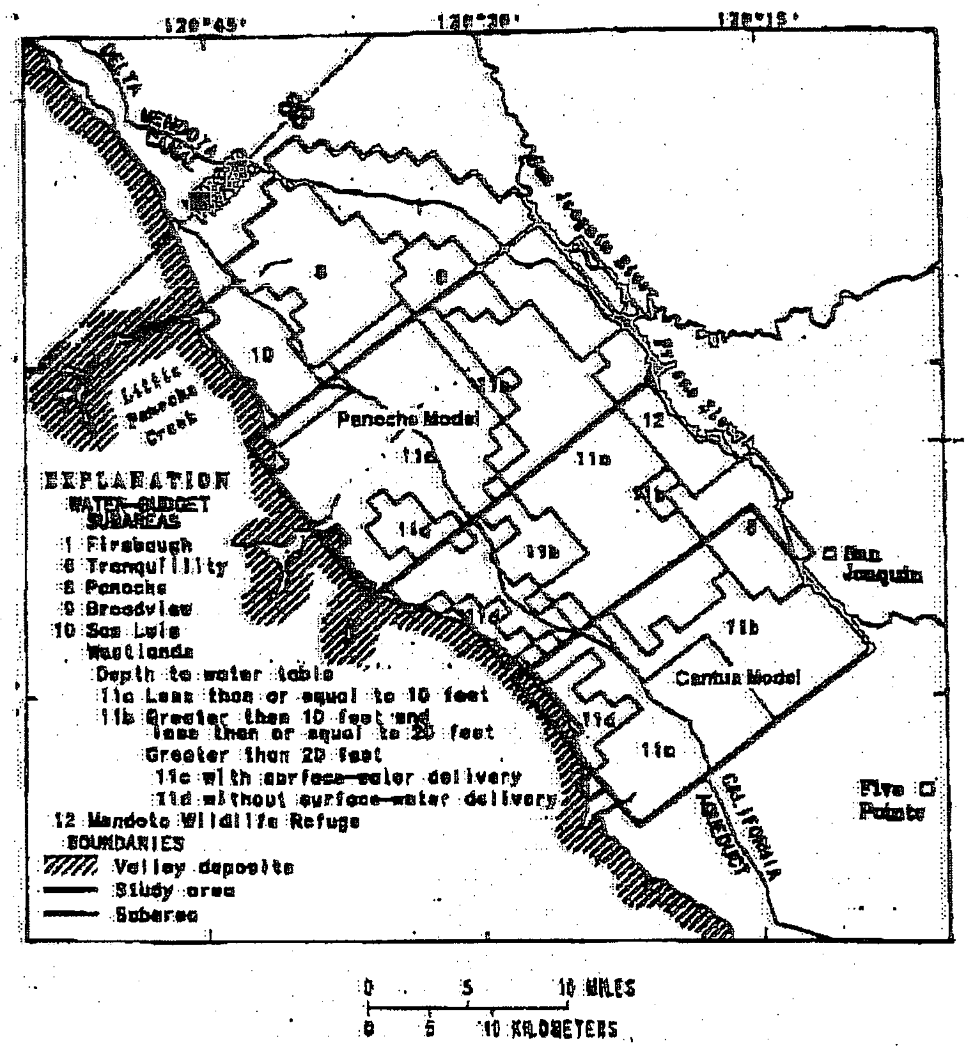
Once this drawdown standard was achieved the value of h was progressively reduced to approximate the case where recharge water fills the depression along the western margins of the San Joaquin Valley (Figure 16). As this is presumably the recharge zone for the confined aquifer, this filling should translate to a rise in the piezometric surface at the western margin. For each new configuration, the Chan solution yields an estimate of the level of pumping that could be maintained while generating the same long-term drawdown at the representative pumping wells as in the base case. The difference in the potential pumping levels represents an estimate of the enhanced level of pumping that could be achieved through an *in lieu* recovery strategy in these portions of the service area.

Figure 18: Delineation of Water Management Units in the Western San Joaquin Valley for Mass Balance Calculations



Figures (19) and (20) present the results of this analysis. The reveal that as the value of the transmissivity increases, approaching the maximum values reported by Williamson

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(1989), the ability to increase the level of groundwater pumping without exceeding the long-term pumping well drawdown associated with the base case is dramatically increased. In addition, the potential for pumping enhancement is proportional to the rise in the piezometric surface on the western margin of the valley.

Figure 19: Results of the Chan Solution for the Panoche Creek Fan Showing the Potential to Increase Pumping as a Function of the Aquifer Transmissivity and the Rise in the Piezometric Surface on the Western Margin of the San Joaquin Valley

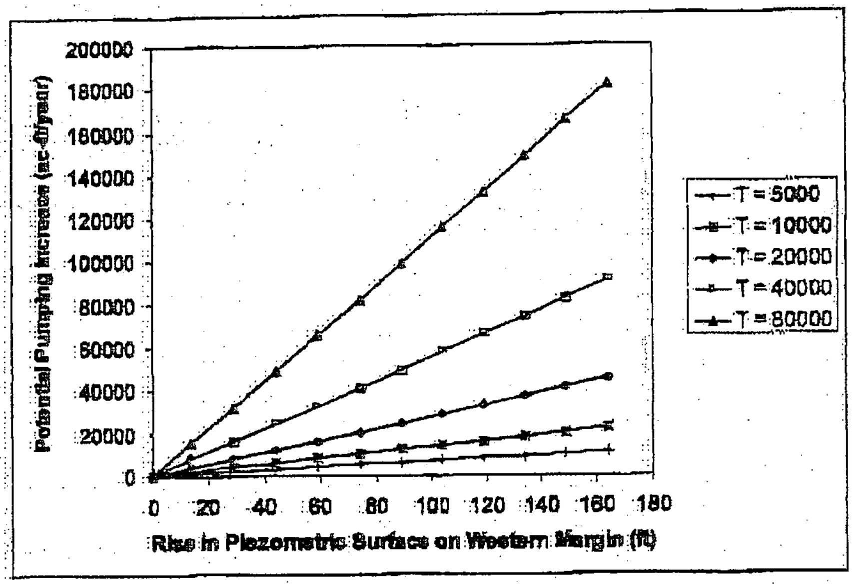
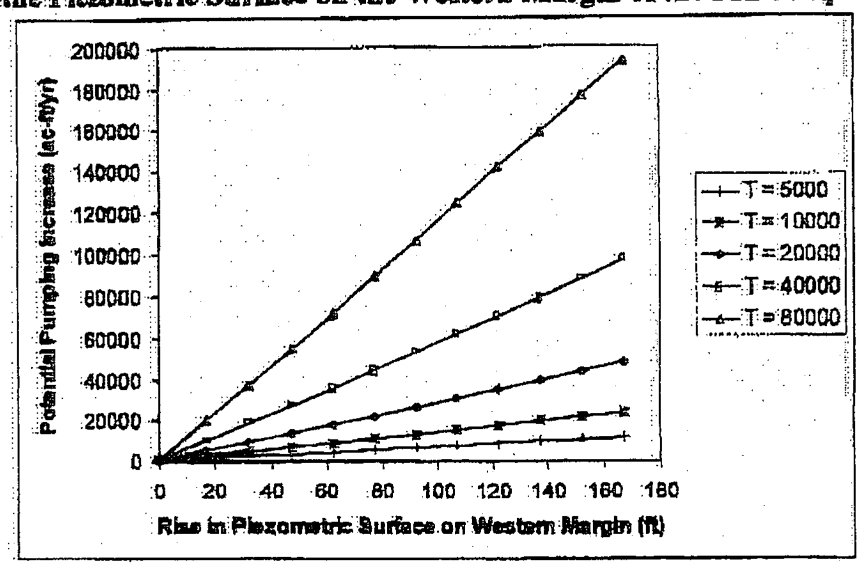


Figure 20: Results of the Chan Solution for the Cantua Creek Fan Showing the Potential to Increase Pumping as a Function of the Aquifer Transmissivity and the Rise in the Piezometric Surface on the Western Margin of the San Joaquin Valley



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According the Chan solution, there is a substantial potential to enhance the *in lieu* recovery of groundwater from the confined aquifer by raising the piezometric surface along the western marginof the valley, particularly when the transmissivity is high. Under the most optimistic assumptions regarding these two parameters, pumping in the two model domains could increase by nearly 360,000 ac-ft/year without generating long-term drawdown in excess of that associated with the base case.

The most ambitious assumption is that the piezometric surface along the western margin could be raised to the point where the slope of the surface goes to zero (h = 0). The configuration of the existing depressions and the amounts of water required to fill them will certainly constrain the degree to which h can be reduced. In order to evaluate this constraint, the storage volumes in the depressions depicted in Figure 18 at varying levels of filling were calculated assuming a specific yield value of 0.08 (Figure 8). These figures reveal that the volume of water required to fill the depression up to the point where the slope of the piezometric surface is eliminated far exceed the volume of enhanced *in lieu* recovery that would be available. There is a physical limit to how much *in lieu* recovery could be enhanced by active recharge of the depressions on the western margins of the valley. Information contained in Figures 21 and 22 yields a rough estimate of when a groundwater banking program might experience severe diminishing returns.

Prior to developing this estimate, however, a frank assessment of the limitation of the data in Figures 21 and 22 must by presented. In essence, these figures contain the results of two separate suites of analyses, the first related to the potential for enhanced pumping (Chan solution) the second related to filling the depression features (geometric analysis of water table data). These analyses are not linked. The Chan solution assumes that the water needed to maintain a more gently sloping piezometric surface is continually available while the geometric analysis assumes that all recharge water goes towards filling static depression features that are immune from losses associated with pumping in the system. As such, both analyses offer optimistic assessments of the potential of groundwater banking in the region. These can be refined only by developing a numerical model of the region to assess the dynamic interactions between active recharge and enhanced pumping under a variety of storage and recovery strategies.

That being said, however, the preliminary analyses conducted here provide a sense of the scale of program that could be contemplated. The point where the required fill volume dramatically diverges from the potential for enhanced pumping represents a firm upper limit on the potential of a program. These points of divergence are presented below.

	Point of Divergence (acre-feet)	
Transmissivity (ft^2/day)	Panoche Creek Fan	Cantua Creek Fan
5000	1100	1400
10000	2800	3500
20000	8500	10,000
40000	24,000	29,000
80000	65,000	65,000

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Figure 21: Comparison of the Potential to Enhance *In Lieu* Recovery of Banked Groundwater in the Panoche Creek Fan by Raising the Western End of the Piezometric Surface and the Water Required to Raise the Bottom of the Depression on theWastern Margin of the San Joaquin Valley

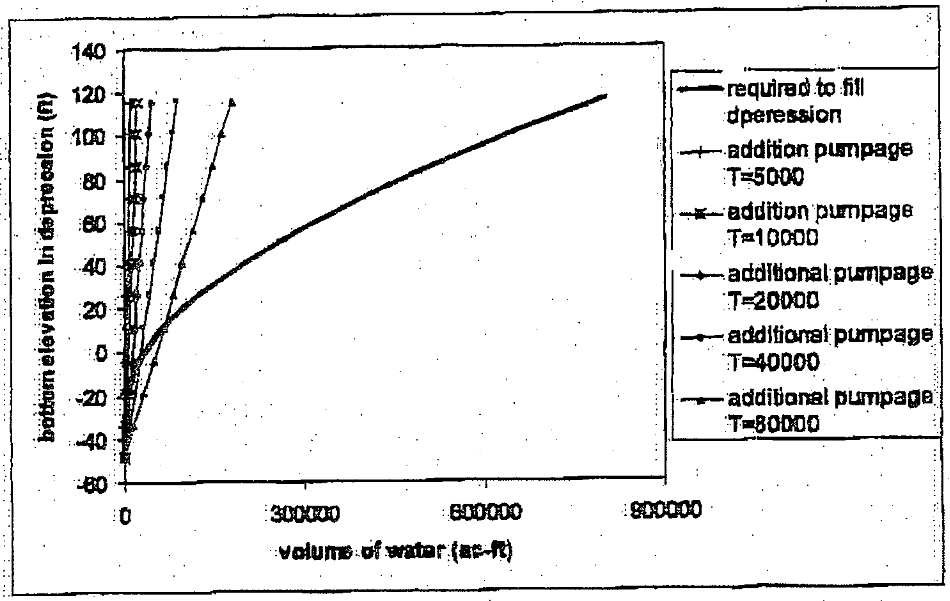
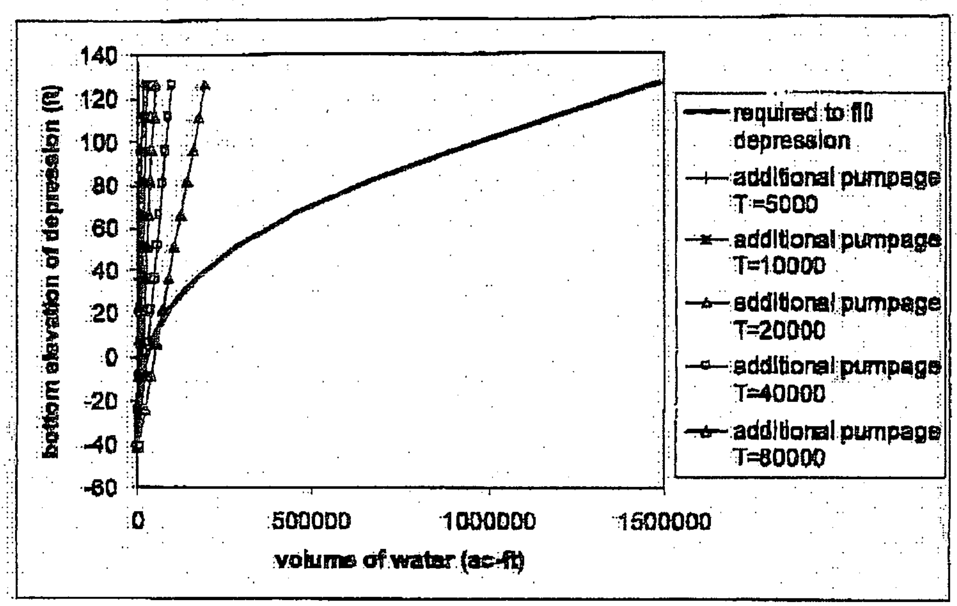


Figure 21: Comparison of the Potential to Enhance *In Lieu* Recovery of Banked Groundwater in the Cantua Creek Fan by Raising the Western End of the Piezometric Surface and the Water Required to Raise the Bottom of the Depression on theWastern Margin of the San Joaquin Valley



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It should be pointed out that the Panoche Creek and Cantua Creek models used in the Chan solution do not extend across the entire area underlain by the two prominent depression features. Much of the depression associated with the Panoche Creek solution actually lies outside the Panoche Creek model below the Little Panoche Creek Fan. The same can be said for the Cantua Creek model where the depression feature extends quite far to the south (Figure 16). While the calculations of fill volumes include the water required to raise the water level in these regions, the two Chan solutions do not account for the enhanced pumping that could take place down fan in these regions. Assuming that we could reasonably double the area where enhanced *in lieu* recovery could be managed, then the total reasonable upper limit on the program in the Authority's service area would range from approximately 5000 acre-feet/year if T equals 5000 ft^2/day to roughly 260,000 acre-feet/year if T equals 80,000 ft^2/day. The lower limit is not very attractive at face value, even less so given that is must be discounted for the inconsistencies in the analysis. The upper limit could be discounted 50% and still provide a significant improvement in the reliability of water supplies in the Authority's service area. The true potential of the program will emerge only from further refinement of parameter estimates in the region and the application of a more dynamic analytical strategy.

8.0 Conclusions

The San Luis and Delta Mendota Water Authority Service Area poses a unique set of challenges to those who would contemplate implementing a program of groundwater banking in the region. The generally poor quality of the region groundwater system combined with constraints placed on the introduction of poor quality water to a conveyance network that the Authority shares with other beneficiaries limits the ability to design a classic active groundwater storage and recovery system. The Authority service area is also fairly unique in that the recharge zone of a confined aquifer that provides substantial water supply to the Authority's customs is fairly accessible from existing conveyance facilities. This set of factors offers the possibility to design a groundwater banking program that combines active recharge supplied by conveying existing Delta supplies through shared infrastructure to recharge pond just up-slope of the San Luis Canal and *in lieu* recovery through managed groundwater pumping across the alluvial fan surfaces down-slope of the canal.

This type of program could require extending the mandate of the Authority beyond the management of surface water alone. If the goal of the Authority is to enhance the overall reliability of water supplies for its customers, the strategy presented here can improve the reliability of the important groundwater component of water balance in the region. The value of this reliability in economic terms is the subject of a companion paper. Designing an institution that can extend its mandate to the management of groundwater will also pose challenges, although follow-on work proposed for this effort should provide a useful framework for working out appropriate details.